Way Point Tracking of a Container Ship by Adaptive Stochastic Sliding Mode Control and Recursive Filters

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Abstract

In this paper, way-point tracking control of a container ship based on LOS method using adaptive stochastic sliding mode controlhas beeninvestigated.Effective control of ships in a designed trajectory is always an important task for ship maneuvering. The design is based on a low and high frequency model of the vessel motion adequate to ship steering. The low frequency model describes the vessel response to rudder control and slowly varying environmental forces. The high frequency model represents the wave induced oscillatory part of the yaw motion.For suppression of high frequency wave disturbances, the nonlinear recursive filter is considered. The uncertainty of model parameters in the presence of disturbances such as waves, wind and currents, dictates the application of techniques in which the nonlinear equations of ship's motion and the presence of unknown parametershave been taken into consideration. In this sense, the adaptive stochastic sliding modedesign is used for solving this problem.The simulation results show the suitability of this technique to compensate the time-varying disturbances effects in way-point tracking control.

Keywords

Adaptive Stochastic Sliding Mode; Recursive Filters; Way-Point Tracking; LOS Guidance

Introduction

The way-point tracking control problem is an issue of high interest in research areas of ship maneuverings. In seaway, the path or trajectory is constructed by using a set of way-points that can be generated according to sail plan and weather data (minimum resistance or energy approach). The way-point tracking control problem is to make the ship follow the path planned with the way-points by controlling the rudder. A widely used method for way-point tracking control is line of sight (LOS) guidance. In this methodology, a LOS vector is computed from the ship position to the next way point for heading control [Fossen (2000)].The way-point tracking control has been improved over several years. Reference [Peterson & Lefeber (2001)] gives a yaw torque control law for ship way-point tracking control problem based on a full state feedback control approach. A new fuzzy autopilot for way-point tracking has beenproposed in [Cheng et al. (2006)]. A way-point guidance algorithm by LOS calculates a dynamic LOS vector norm in order to minimize the cross track error, is presented in [Moreira et al. (2007)]. In reference [Aguiar and Pascoal (2007)] integrator backstepping and Lyapunov based techniques are used for way-point tracking of under actuated autonomous underwater vehicles (AUVs) in the presence of constant unknown ocean currents and parametric modeling uncertainty. Model predictive control (MPC) for a way-point tracking under actuated surface vessels with input constraints wasproposed in [Ryeko, Jing (2010)]. In order for the control action to render good helmsman behavior, a MPC scheme with line-of-sight (LOS) path generation capability is formulated. In [Jun & He (2011)] an adaptive output feedback controller based on neural network feedback–feed forward compensator (NNFFC) which drives a surface ship at high speed to track a desired trajectory has beendesigned. A hybrid model was proposed in [Wu & Penga (2012)] to represent the ship's tracking dynamic behavior. A single-input single-output nonlinear time series model has beenbuilt to characterizethe responses between the ship's heading angle deviation and its rudder angle.

Sliding mode control is based on the Lyapunov stability theorem and the LaSalles invariant principle, often referred toas variable structure.Sliding mode control (SMC) is a control method that switches between two distinctly different control laws depending on the state of the system. The salient advantages of sliding model control are: i) fast response and good transient performance; ii) its robustness against a large class of perturbations or model uncertainties and its ability to reject external

disturbances; and iii) the possibility of stabilizing some complex nonlinear systems which are difficult to stabilize by continuous state feedback laws.

The SMC can be used as a supervisory controller along with the adaptive control. Adding the SMC to the control scheme will enable the overall controller to adapt over time as well as reject external disturbances and protect against parameter variations [Ebel (2011)], [Chan (2000)], [Lokukaluge & Perera (2012)]. This is of great importance in the case of ship control systems in which there are uncertainty of nonlinear model parameters in the presence of disturbances such as waves, wind and currents.

The heading measurement is corrupted with colored noise due to wind, waves and ocean currents as well as sensor noise. However, only the slowly varying disturbances should be counteracted by the propulsion system, whereas the oscillatoric motion due to the waves should not enter the feedback loop. This is done by using so called wave filtering technique which separates the heading measurement into a low frequency and wave frequency estimate [Ricardo, Guedes (2009)]. For this purpose, the recursive filtersis utilized.

In this paper, the problem of way-point tracking of container ship is considered. The disturbances such as wave, winds and currents are regarded. These disturbances are time-varying and control problem has been solved using recursive filters and adaptive stochastic sliding modemethod.

The remainder of this paper is organized as follows. Section 2 deals with the modeling of ship and disturbances, Section 3 describes designing nonlinear controller, in section 4 the LOS guidance system is explained briefly, Section 5 discusses results and, finally, andthe conclusion is made in the last section.

Equations of Motion and Disturbances Modelling

Equations of Motion

Ship dynamics is obtained by applying Newton's laws. The marine vehicle has 6 degrees-of-freedom (DOF) since six independent coordinates are necessary to determine the spatial position and orientation of a rigid body. The six different motion components are called: surge, sway, heave, roll, pitch, and yaw. Accordingly, the most generally used notation for these quantities are: $x, y, z,\ \phi, \theta$andψ: "Fig. 1"shows all six coordinate definitions and the most generally adopted reference frame. The position and orientation of the ship are described relative to the inertial reference frame O_E - $x_E y_E z_E$ (Earth-fixed reference frame). The general ship equations of motion can be expressed in compact form as [Velagica et al. (2003)]

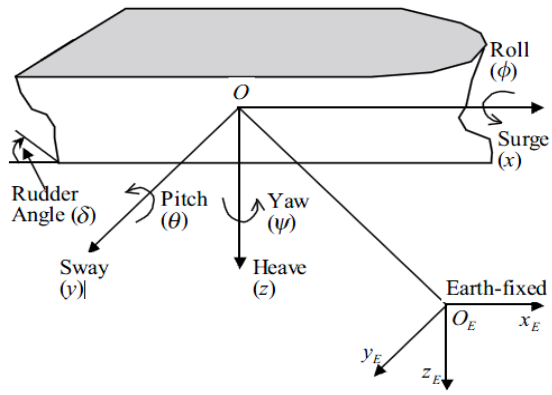

FIG. 1 BODY- AND EARTH-FIXED REFERENCE FRAMES

$$M\dot{v} + C(v)v = \tau \tag{1}$$

Where M is the inertia matrix, $C(v)$ is a matrix of Coriolis and centripetal terms, $v = [u, v, w, p, q, r]^T$ is the body-fixed (ship) linear and angular velocities vector and $\tau = [X, Y, Z, K, M, N]^T$ is a generalized vector of external forces and moments. For the course-keeping and the track-keeping problems, only the horizontal-plane ship motion is used.

Due to that, 6DOF model is simplified and reduced to 3DOF model. Assuming that the coordinate of body-fixed frame origin is set in the center line of the ship ($y_G = 0$), the mass distribution is homogeneous, the xz-plane is symmetrical, and that the influence of motions in the z-direction (heave), rotation about x-axis (roll) and y-axis (pitch) to the motion in horizontal plane can be neglected, the non-linear ship equations of motion are (Fossen, 1994):

$$\text{Surge:}\ m(\dot{u} - vr - x_G r^2) = X \tag{2}$$

$$\text{Sway:}\ m(\dot{v} + ur + x_G \dot{r}) = Y \tag{3}$$

$$\text{Yaw:}\ I_z \dot{r} + m x_G(\dot{v} + ur) = N \tag{4}$$

Where m is mass of the ship, u and v are surge and sway velocities, respectively, r is the yaw rate, I_z is moment of inertia about the z-axis, X and Y are forces in the x- and y-axis direction, respectively, N is a moment around the z-axis and $r_G = [x_G, y_G, z_G]$ is the center of the gravity.

$$X = X(u, v, r, \dot{u}, \dot{v}, \dot{r}, \delta) \tag{5}$$

$$Y = Y(u, v, r, \dot{u}, \dot{v}, \dot{r}, \delta) \tag{6}$$

$$N = N(u, v, r, \dot{u}, \dot{v}, \dot{r}, \delta) \tag{7}$$

Disturbances Modeling

While moving in oceans, ships' motions are often influenced by environmental disturbances, therefore

in order to control ships effectively, it is necessary to model the environmental disturbances such aswinds, ocean currents and waves. Influence of each type of disturbances is derived separately and then the principle of superposition is applied to get the influences of environmental disturbances [Fossen (1994)].

1) *Influences of Wind*

Forces and moments generated by the wind are given by the following system of equations:

$$X_a = (1/2)\rho_A C_x(\theta_a) A_T V_A^2 \quad (8)$$

$$Y_a = (1/2)\rho_A C_y(\theta_a) A_l V_A^2 \quad (9)$$

$$N_a = (1/2)\rho_A C_n(\theta_a) L A_L V_A^2 \quad (10)$$

These forces and moments are added to right hand side of the "Equations (2) to (4)".

Here, ρ_A is air density; A_T, A_L are transverse and longitudinal projected areas, respectively; θ_a, is wind relative direction; V_A is relative wind speed and C_x, C_y, C_n are forces and moment coefficients in X, Y, N directions, respectively. The relation between wind relative direction and forces and moment coefficients are shown in Fig. 2.

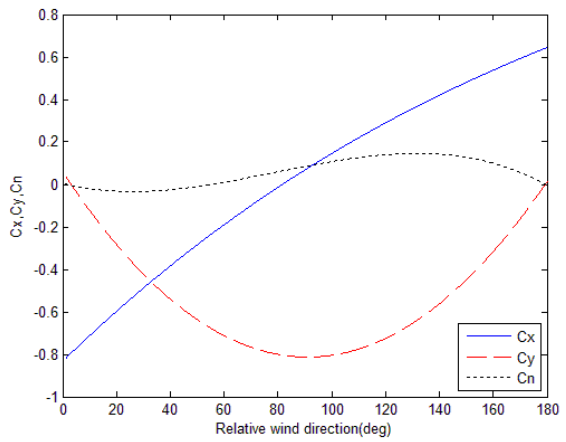

FIG. 2 RELATION BETWEEN RELATIVE WIND DIRECTION AND FORCES AND MOMENT

2) *Ocean Currents*

The two-dimensional current model is used here. The Earth-fixed current components can be described by two parameters: the average current speed V_c and direction of the currents γ_c. The body-fixed components can be computed from

$$u_c = V_c \cos(\gamma_c - \psi) \quad (11)$$

$$v_c = V_c \sin(\gamma_c - \psi) \quad (12)$$

The average sea current velocity for computer simulations can be generated by using a first-order Gauss–Markov process, described by the following differential equation:

$$\dot{V}_c(t) + \mu_0 V_c(t) = w(t) \quad (13)$$

Where $w(t)$ is a zero mean Gaussian white noise sequence and $\mu_0 \geq 0$ is a constant. This process must be limited such that $V_{min} \leq V_c(t) \leq V_{max}$ in order to simulate realistic sea currents.

3) *Wind-Generated Wave*

The oscillatoric motion of the waves can be described by (Fossen, 1998):

$$\psi_H(s) = K_w s/(s^2 + 2\zeta\omega_0 s + \omega_0^2) \times w_H(s) \quad (14)$$

Where $w_H(s)$ is a zero-mean Gaussian white noise process, ω_0 is a wave frequency (modal frequency), ζ is a damping coefficient and K_w is a gain constant. The gain constant is defined as $k_w = 2\zeta\omega_0\sigma_w$; where σ_w is a constant describing the wave intensity.

The transfer function in "Equation (14)" is usually represented by the state space model

$$\dot{\xi}_H = \psi_H \quad (15)$$

$$\dot{\psi}_H = -2\zeta\omega_0\psi_H - \omega_0^2\xi_H + K_w w_H$$

Designing Nonlinear Controller

Nonlinear Model of Ship

The control system is designed for steering a ship on the course. In this system, the controlled parameter is the ship course, *ψ(t),* while the controlling parameter is the rudder angle, *δ(t).* For control purpose, the Bech's model is used obtained from the second-order Nomoto model, in which the angular velocity $\dot{\psi}(t)$ was replaced by a nonlinear manoeuvring characteristic $H(\dot{\psi}(t))$, the coefficients of which can be determined from a spiral test that is used in many papers and described in (Fossen, 2000). The obtained model is given by the following equation (Amerongen, 1982):

$$\dddot{\psi}(t) + \left(\frac{1}{T_1} + \frac{1}{T_2}\right)\ddot{\psi}(t) + \frac{1}{T_1 T_2} H\left(\dot{\psi}(t)\right)$$

$$= \frac{K}{T_1 T_2}\left(T_3\dot{\delta}(t) + \delta(t)\right) \quad (16)$$

Where $H(\dot{\psi}(t))$ is approximated by the following function:

$$H(\dot{\psi}(t)) = \alpha\dot{\psi}(t)^3 + \beta\dot{\psi}(t) \quad (17)$$

Where α and β are real constants. Commonly, α and β are calculated based on a spiral test off-line, but in this article, because of the presence of time-varying disturbances, the spiral test is not helpful to obtain these parameters [Krestic et al. (1995)]. Identification of these parameters as well as the control procedure is implemented by adaptive stochastic sliding mode. To simplify control design, the Bech model is reduced to the Norrbin model given by:

$$T\dddot{\psi}(t) + H\left(\dot{\psi}(t)\right) = K\,\delta(t) \quad (18)$$

Where

$$T = T_1 + T_2 - T_3 \quad (19)$$

In order to carry out the system description by the nonlinear state equations, it is preferable to define the following state variables : $x_1 = \psi_L$ (yaw angle), $x_2 = \dot{\psi} = r_L$ (yaw rate), and the output $y = x_1$. The kinematic equations of ship dynamics are

$$\dot{x}_1 = x_2 \quad (20)$$

$$\dot{x}_2 = a_1 x_2^3 + a_0 x_2 + du \quad (21)$$

$$u = \delta \quad (22)$$

The coefficient's values are defined as:

$$a_1 = -\alpha/T \quad (23)$$

$$a_0 = -\beta/T \quad (24)$$

$$d = K/T \quad (25)$$

Recursive Filters

By combining the low frequency (LF) model representing the motion of the vessel and a high frequency (HF) 1st-order wave induced motion, the heading angle can be expressed as:

$$\psi = \psi_L + \psi_H + v_H \quad (26)$$

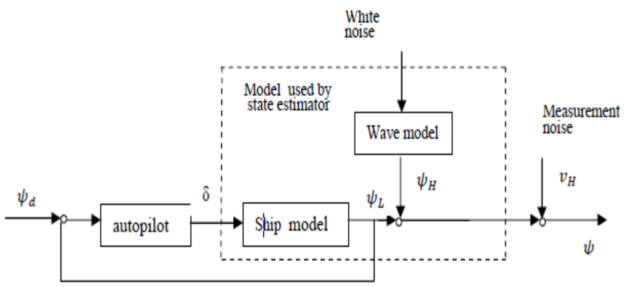

FIG. 3 LOW FREQUENCY (LF) AND HIGH FREQUENCY (HF) SUB MODELS

Where v_H represents zero-mean Gaussian measurement noise. The resulting model is shown in Fig. 3. In most ship applications, it is important that the contribution from the high frequency wave motion is suppressed. If not, wave disturbances can cause wear on the rudder, propeller and the thruster actuators. One of the methods for suppression of high frequency wave disturbances is state estimation.

The ship wave system is described by the state $x = [\psi_L, r_L, \xi_H, \psi_H]^T$, input u = δ, and process noise $w = [w_L, w_H]^T$ .It isassumed that $w \sim N(0, Q)$ and $v \sim N(0, R)$. The nonlinear model is given by:

$$x(n+1) = \phi[x(n), n] + G[x(n), n]w(n) + B(n)u(n)$$

$$z(n) = h[x(n), n] + v(n) \quad (27)$$

$$G = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & K_w \end{bmatrix},\ B = \begin{bmatrix} 0 \\ K/T \\ 0 \\ 0 \end{bmatrix},\ h = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

ϕ is the nonlinear function of combination ofthe "Equations (15), (20) and (21)". The state estimation in discrete nonlinear dynamic system has been appliedby recursive filters by the following equation (Schweppe, 1973)

$$\hat{x}(N+1|N+1) = \hat{x}(N+1|N) + B(N)u(N) + K(N+1) \times \{z(N+1) - h[\hat{x}(N+1|N), N+1]\}$$

$$\hat{x}(N+1|N) = \phi[\hat{x}(N|N), N]$$

$$K(N+1) = \Sigma(N+1|N+1) \times H^{(1)'}[\hat{x}(N+1|N), N+1]\, R^{-1}(N+1)$$

$$\Sigma(N+1|N+1) = \{H^{(1)}[\hat{x}(N+1|N), N+1] \times R^{-1}(N+1)[\hat{x}(N+1|N), N+1] + \Sigma^{-1}(N+1|N)\}^{-1}$$

$$\Sigma(N+1|N) = \phi^{(1)}[\hat{x}(N|N), N]\Sigma(N|N)\phi^{(1)'}[\hat{x}(N|N), N] + G[\hat{x}(N|N), N]Q(N)G'[\hat{x}(N|N), N]$$

$$\Sigma(0|0) = \Psi$$

$$\hat{x}(0|0) = 0 \quad (28)$$

The control objectives are:

(1) To force the output $y = x_1 = \psi$ of the system to asymptotically track the reference output $y_r(t) = \psi_r(t)$.

(2) To keep the rudder angle in the acceptable range.

Adaptive Stochastic Sliding Mode procedure

The system is governed by stochastic differential equations in the Ito sense as

$$dx_1 = x_2 dt$$

$$dx_2 = [a_1 x_2^3 + a_0 x_2]dt + U(t)dt + dB(t) \quad (29)$$

Where

$$E[dB(t)] = 0,$$

$$E[dB(t_1)dB(t_2)] = \begin{cases} 2Ddt, & t = t_1 = t_2 \\ 0, & t_1 \neq t_2 \end{cases} \quad (30)$$

We use the sliding function $S = x_2 + \lambda(x_1 - \psi_r)$ ($\lambda > 0$). After obtaining the nominal sliding mode control, we focus on the following control

$$U(t) = -\hat{a}_0 x_2 - \hat{a}_1 x_2^3 - \lambda x_2 - kS \quad (31)$$

Where $\hat{a}_0$ and $\hat{a}_1$ are estimates of $a_0$and a_0, $k > 0$, and $-kS$is the 'switching' term. Instead of x_1 and x_2,$\hat{\psi}(t)$ and $\hat{r}(t)$ which are obtained from state estimator should be replaced.

Consider a Lyapunov function$V = E[V_d]$where:

$$V_d = \frac{1}{2}S^2 + \frac{1}{2\gamma}(\hat{a}_0 - a_0)^2 + \frac{1}{2\eta}(\hat{a}_1 - a_1)^2 \quad (32)$$

Clearly $V > 0$. To evaluate the time derivative of V_d by following Ito lemma, we have

$$dV_d = SdS + \frac{1}{\gamma}(\hat{a}_0 - a_0)d\hat{a}_0 + \frac{1}{\eta}(\hat{a}_1 - a_1)d\hat{a}_1$$

$$= S[(a_0 - \hat{a}_0)x_2 + (a_1 - \hat{a}_1)x_2^3 - kS + 2D]dt +$$

$$SdB(t)+\frac{1}{\gamma}(\hat{a}_0 - a_0)d\hat{a}_0 + \frac{1}{\eta}(\hat{a}_1 - a_1)d\hat{a}_1 \quad (33)$$

Let

$$d\hat{a}_0 = \gamma S x_2 dt \quad (34)$$

$$d\hat{a}_1 = \eta S x_2^3 dt \quad (35)$$

These define rules for updating parameter estimates $\hat{a}_0$and $\hat{a}_1$. We have

$$dV_d = [-kS^2 + 2D]dt + SdB(t) \quad (36)$$

Hence, we obtain

$$\dot{V} = dE[V_d]/dt = -kE[S^2] + 2D \quad (37)$$

In the absence of stochastic excitation with $D = 0$, we have $\dot{V} < 0$. This shows that V is uniformly bounded.

Los Guidance

Systems for guidance consist of waypoints that are used to generate a trajectory (path) for the ship. A widely used method for path control is LOS guidance. In this methodology, a LOS vector from the ship to the next way point is computed. The desired heading angle as a set point for autopilot system can be calculated through:

$$\psi_d(t) = tan^{-1}[\,(y_d(k) - y(t))/(x_d(k) - x(t))] \quad (38)$$

Care must be taken to select the proper quadrant for ψ_d. The next way point can be selected based on whether the vessel lies within a circle of acceptance with radius ρ_0 around the way-point $(x_d(k), y_d\,(k)\,)$. Moreover, if the vessel location $(x(t), y(t))$ at the time t satisfies:

$$[x_d(k) - x(t)]^2 + [y_d(k) - y(t)]^2 \leq \rho_0{}^2 \quad (39)$$

The next way point $(x_d(k+1), y_d(\mathrm{k}+1))$ should be selected. A guideline could be to choose ρ_0 equal to two shiplengths, that is $\rho_0 = 2\mathrm{L}$ [Fossen (1998)].

Simulation Results and Analysis

Simulation results are considered for a container ship that the values of the parameters used during simulation are chosen from example 1.3 in[Fossen (1994)] and shown in Figs 4–9. For the numerical simulations, the fourth-order Runge-Kutta method with time-step $\mathrm{h} = 10^{-4}$ is used. Total heading angle is shown in Fig. 4 that is obtained by stochastic sliding mode control without using recursive filters. The comparisons of LF heading angle with two control methods that are obtained from state estimation are shown in Fig. 5. Fig. 6 and Fig. 7 show the rudder angle of ship in the presence of time-varying disturbances by spiral test + PID method and adaptive stochastic sliding mode respectively, also the recursive filter is applied to both of them. Fig. 8 gives the way-point tracking course for the adaptive stochastic sliding mode autopilot with recursive filter in the presence of disturbances and without disturbances. These two courses are close to each other. Fig. 9 shows the updating parameters in adaptive stochastic sliding mode control.

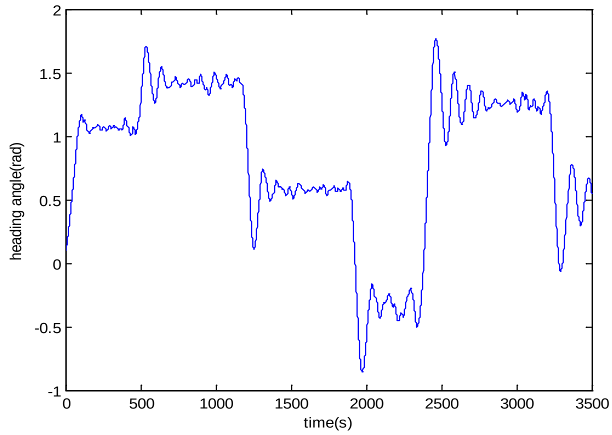

FIG. 4 COMBINING THE LOW FREQUENCY (LF) MODEL REPRESENTING THE MOTION OF THE VESSEL AND A HIGH FREQUENCY (HF) WAVE INDUCED MOTION.

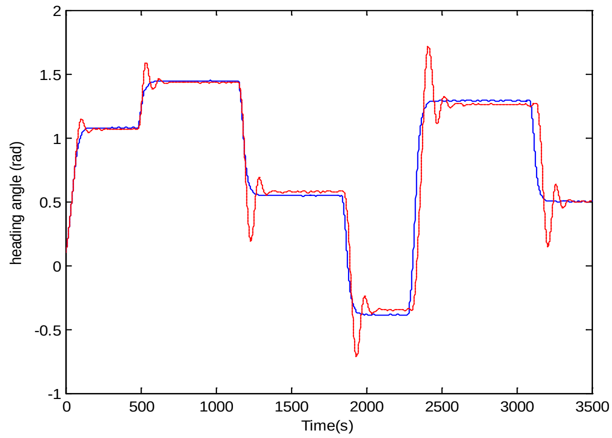

FIG. 5 COMPARISON OF HEADING ANGLE (LF) : SPIRAL TEST FOR OBTAINING SHIP MODEL PARAMETERS + PID CONTROLLER (DASHED LINE) AND ADAPTIVE STOCHASTIC SLIDING MODE(SOLID LINE)

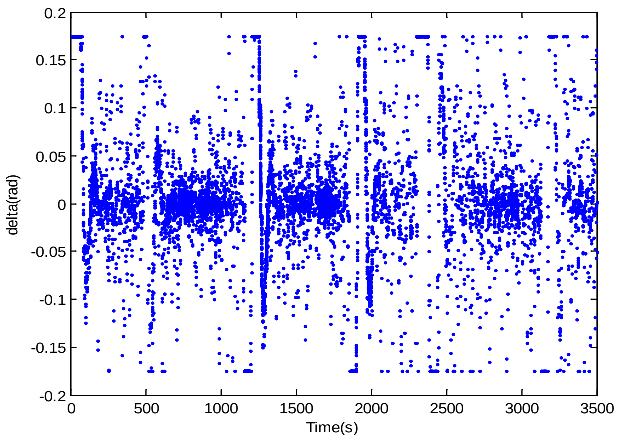

FIG. 6 SHIP RUDDER ANGLE IN THE PRESENCE OF DISTURBANCES BY SPIRAL TEST +PID

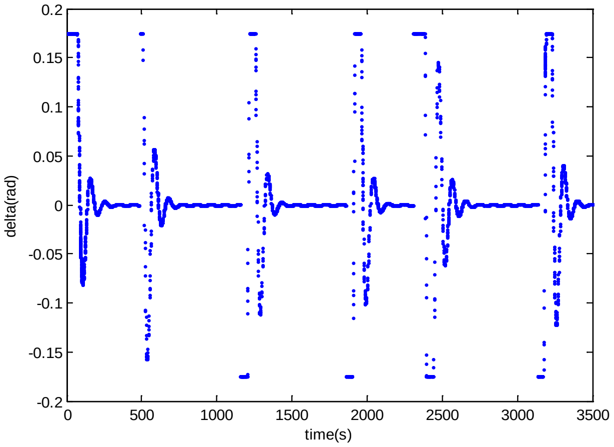

FIG. 7 SHIP RUDDER ANGLE IN THE PRESENCE OF DISTURBANCES BY ADAPTIVE STOCHASTIC SLIDING MODE.

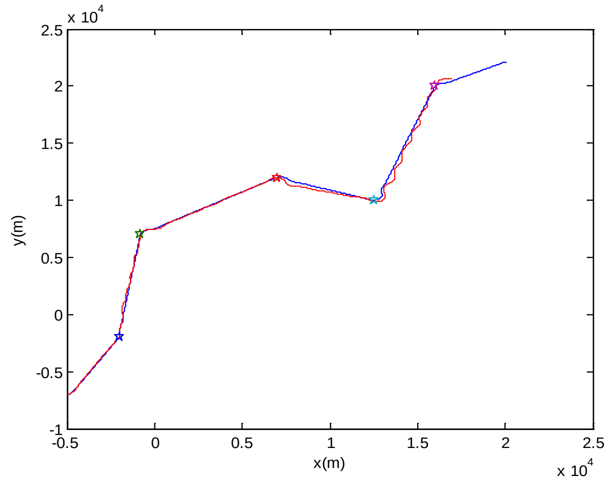

FIG. 8 COMPARISON OF SIMULATION RESULTS OF WAY-POINT TRACKING : IN PRESENCE OF DISTURBANCES (DASHED LINE), WITHOUT DISTURBANCES (SOLID LINE).

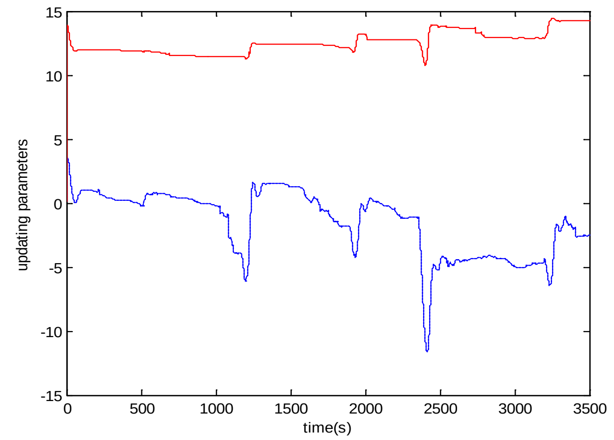

FIG. 9 UPDATING THE PARAMETERS a_1,a_0

Conclusions

The paper has considered way-point tracking system in the presence of time-varying disturbances with adaptive stochastic sliding mode approach. Also for suppression of high frequency of rudder angle, the recursive filter is used. Even though PID control is widely used throughout industrial application, it handles parameter variations and external disturbances poorly, whereas the adaptive stochastic sliding mode control is known for its robustness against these uncertainties. The maximum distance of way-point tracking course for the adaptive stochastic sliding mode autopilot in the presence of disturbances and without disturbances is 300 m that is acceptable for this container ship with length 175 m.To compare the adaptive stochastic sliding mode control with PID, the recursive filter is applied to both of them. The results show the better performance in terms of transient and saturation in the control input for the adaptive stochastic sliding mode in comparison with PID (that the model parameters are obtained off-line by spiral test) because the model parameters are updated duringprocedure. Maximum rudder angle for this container ship is 10 (deg) that in adaptive stochastic sliding mode control, the rudder angle is saturated in the shorter time compared to PID control.So this algorithm iseffectively implementedin the way-point tracking control.

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